

A SEARCH FOR SUB-MILLIMETER H₂O MASERS IN ACTIVE GALAXIES – THE DETECTION OF 321 GHz H₂O MASER EMISSION IN NGC 4945

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ABSTRACT

We present further results of a search for extragalactic submillimeter H₂O masers using the Atacama Large Millimeter/Submillimeter Array (ALMA). The detection of a 321 GHz H₂O maser in the nearby Type 2 Seyfert galaxy, the Circinus galaxy, has previously been reported, and here the spectral analysis of four other galaxies is described. We have discovered H₂O maser emission at 321 GHz toward the center of NGC 4945, a nearby Type 2 Seyfert. The maser emission shows Doppler-shifted velocity features with velocity ranges similar to those of the previously reported 22 GHz H₂O masers, however the non-contemporaneous observations also show differences in velocity offsets. The sub-parsec-scale distribution of the 22 GHz H₂O masers revealed by earlier VLBI (Very Long Baseline Interferometry) observations suggests that the submillimeter masers could arise in an edge-on rotating disk. The maser features remain unresolved by the synthesized beam of $\sim 0''.54$ (~ 30 pc) and are located toward the 321 GHz continuum peak within errors. A marginally detected (3σ) high-velocity feature is redshifted by 579 km s^{-1} with respect to the systemic velocity of the galaxy. Assuming that this feature is real and arises from a Keplerian rotating disk in this galaxy, it is located at a radius of ~ 0.020 pc ($\sim 1.5 \times 10^5$ Schwarzschild radii), which would enable molecular material closer to the central engine to be probed than the 22 GHz H₂O masers. This detection confirms that submillimeter H₂O masers are a potential tracer of the circumnuclear regions of active galaxies, which will benefit from higher angular resolution studies with ALMA.

Keywords: galaxies: active — galaxies: nuclei — galaxies: individual (NGC 4945) — galaxies: ISM — masers — submillimeter: galaxies

1. INTRODUCTION

Maser emission at the H₂O 6₁₆–5₂₃ transition (rest frequency, $\nu_{\text{rest}} = 22.23508 \text{ GHz}$) occurs over a wide range of physical conditions with kinetic temperatures of $T_k = 200 - 2000 \text{ K}$, hydrogen densities of $n(\text{H}_2) = 10^8 - 10^{10} \text{ cm}^{-3}$, and H₂O densities of $n(\text{H}_2\text{O}) = 10^3 - 10^5 \text{ cm}^{-3}$ (e.g., [Elitzur et al. 1989](#); [Neufeld et al. 1995](#); [Humphreys et al. 2005](#)). Extragalactic 22 GHz H₂O masers provide important information on the geometry and kinematics of the central few parsecs of active galactic nuclei (AGN) in terms of dense molecular gas. Submillimeter H₂O maser transitions at the 321.226 GHz (10₂₉–9₃₆) and 325.153 GHz (5₁₅–4₂₂) transitions are strongly inverted under more restricted physical conditions (e.g., $T_k > 1000 \text{ K}$) ([Deguchi 1977](#); [Neufeld & Melnick 1990](#); [Neufeld & Melnick 1991](#)). The first detection of a 321 GHz (10₂₉–9₃₆) H₂O maser in a Galactic star-forming region was achieved by [Menten et al. \(1990a\)](#). Subsequent detections of (sub)millimeter H₂O masers at 183.308, 321.226, and 325.153 GHz in Galactic sources ([Menten et al. 1990a](#); [Menten & Melnick 1991](#); [Humphreys 2007](#)) have inspired similar searches toward active galaxies.

The studies of extragalactic sub-millimeter H₂O masers were pioneered by [Humphreys et al. \(2005\)](#), who discovered extragalactic sub-millimeter H₂O masers at the 183 GHz (3₁₃–2₂₀) and 439 GHz (6₄₃–5₅₀) transitions toward the nuclear region of the Type 2 Seyfert/LINER galaxy NGC 3079 using the Submillimeter Array (SMA) and James Clerk Maxwell Telescope (JCMT). The detection of 183 GHz H₂O emission from the merging galaxy Arp220, which hosts two nuclei but no active nucleus in its center, has also been reported ([Cernicharo et al. 2006](#)). [Hagiwara et al. \(2013\)](#)

reported the first extragalactic detection of 321 GHz H_2O maser emission toward the center of the Circinus galaxy, which has a Type 2 Seyfert nucleus, using the Atacama Large Millimeter/submillimeter Array (ALMA).

These studies suggest that extragalactic sub-millimeter H_2O masers may be common in AGN and could be associated with AGN activity or trace a circumnuclear disk around the AGN like the nuclear H_2O megamasers at 22 GHz (e.g., Miyoshi et al. 1995), although the 183 GHz H_2O emission in Arp220 arises from a star-forming site in the galaxy rather than AGN activity (Cernicharo et al. 2006). Following our previous study of 321 GHz maser emission in the Circinus galaxy, we present here the results of a search for 321 GHz and 325 GHz H_2O masers toward several AGN, conducted with ALMA. Throughout this article, cosmological parameters of $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_M = 0.27$ are adopted. The optical velocity definition is adopted throughout this article and the velocities are calculated with respect to the Local Standard of Rest (LSR).

2. SAMPLE SELECTION

In this program, we concentrated our search for extragalactic submillimeter H_2O masers at the 321.226 GHz transition from the known H_2O nuclear masers with the strongest maser flux densities at 22 GHz (Claussen & Lo 1986; Greenhill & Gwinn 1997; Dos Santos & Lépine 1979; Braatz et al. 2003), and additionally searched for the 325.153 GHz transition from the megamaser galaxy, NGC 5793 (Hagiwara et al. 1997). It is generally understood that 321 GHz and 325 GHz H_2O masers exist in circumstellar envelopes in Galactic star-forming regions (e.g., Menten et al. 1990a; Menten & Melnick 1991), while the 325 GHz H_2O emission is known to be strongly attenuated by water vapor absorption in atmosphere. However, the attenuation of the 325 GHz H_2O line is less significant for distant galaxies due to the redshift of the H_2O line velocity, and so we included NGC 5793, at distance of 51 Mpc, in our list (Table 1). All the galaxies in our list contain 22 GHz nuclear masers which are sub-categorized as disk masers, having characteristic spectra implying the presence of a disk around a nucleus (e.g., Greenhill et al. 2009). The presence of a nuclear edge-on disk in the nuclear region makes the detections of submillimeter H_2O maser more likely (e.g., Humphreys et al. 2005). However, it is also possible that submillimeter maser emission may arise from extragalactic star-forming sites like the 22 GHz H_2O masers in star-forming galaxies (e.g., Greenhill et al. 1993; Hagiwara 2007).

3. OBSERVATIONS AND DATA REDUCTION

We conducted spectral-line observations at the 321 GHz and 325 GHz transitions toward five galaxies in ALMA Band-7 during the Cycle-0 time between 2012 June 2 and June 6 under the experiment code #2011.0.00121.S (PI: Hagiwara). Hagiwara et al. (2013) have previously reported the detection of 321 GHz H_2O maser emission in the nearby Circinus galaxy arising from this set of observations, and preliminary results from this fuller study were presented by Hagiwara et al. (2015). A summary of the observations is given in Table 1, including the target galaxies, observation dates, and the number of antennas employed in each observation. We set the detection threshold at the 5σ level, with the observed 1σ noise level of $\sim 20 \text{ mJy}$ resulting in a flux-density limit of about $100 \text{ mJy beam}^{-1}$ for all sources. This was considered to be sufficient to search for new submillimeter H_2O masers from the known 22 GHz megamaser galaxies having a disk or disk-like structure. The durations of the observations ranged from 20 to 50 minutes (approximately 5–20 minutes on-source), depending on the target source. In our all observations, a single dual polarization spectral window (1.875 GHz bandwidth) in the Frequency Division Mode was employed: The single 1.875 GHz bandwidth was divided into 3840 spectral channels, yielding spectral resolutions of 488 kHz or $\sim 0.45 \text{ km s}^{-1}$ at the observed frequency of 319.4–321.5 GHz. The resultant total velocity coverage was $\sim 1760 \text{ km s}^{-1}$, centered near each galaxy’s systemic velocity. We conducted phase-referencing observations using a bright phase-reference source within $\sim 10^\circ$ of the target sources. Data calibration was performed using the Common Astronomy Software Applications (CASA). Amplitude calibration was performed using observations of Titan or Uranus, and the bandpass calibration was made using the bright quasar, either 3C 279 or 3C 454.3, that was nearest to the target source. Flux-density errors of 10 percent are adopted, as stated in the capabilities of Cycle 0 observations for Band 7. The image analysis was performed using both CASA and the Astronomical Image Processing Software (AIPS). After phase and amplitude calibration, the 321/325 GHz continuum emission was subtracted from the spectral line visibilities using line-free channels prior to the imaging and CLEAN deconvolution. The line emission from each galaxy was separated out from the continuum emission. The synthesized beam sizes (natural-weighting) and the beam position angles used in the CLEAN process and the resultant rms noise levels in the spectral line images are listed in Table 1.

4. RESULTS

We searched for maser emission in each AGN within a field of view of $\sim 18''$, centered on the phase-tracking center of each source and within the observed velocity range. Fig. 1 shows spectra at 321 GHz from the four AGN, NGC 1068,

NGC 1386, NGC 4945, and NGC 5793, and at 325 GHz from NGC 5793. The only emission exceeding a signal-to-noise ratio (SNR) of 5 is seen in NGC 4945, as reported by Hagiwara et al. (2015). The detection of H₂O emission toward NGC 4945 is reminiscent of that towards the Circinus galaxy reported in our earlier study (Hagiwara et al. 2013). Given the narrow line-widths of the H₂O emission and the fact that it is unresolved at the angular resolution of our observations, it is most likely that the detected H₂O emission has a maser origin, as in the case of Circinus. Fig. 2 displays the spectrum of the H₂O maser emission and the 321 GHz continuum emission in NGC 4945. Several 321 GHz H₂O maser features were detected in NGC 4945, with peak flux densities of ~ 45 mJy beam⁻¹ at $V_{\text{LSR}} = 714.4$ km s⁻¹ and ~ 50 mJy beam⁻¹ at $V_{\text{LSR}} = 718.9$ km s⁻¹. All these features are detected with a SNR > 5. In Fig. 1, the detected H₂O emission of NGC 4945 comprises distinct features that are redshifted from the systemic velocity of the galaxy ($V_{\text{LSR}} = 556$ km s⁻¹). The feature at $V_{\text{LSR}} = 714.4$ km s⁻¹, which shows the strongest peak, is redshifted by 162.9 km s⁻¹ from the systemic velocity. Most of the other prominent features lie in the redshifted velocity range of $V_{\text{LSR}} = 711\text{--}722$ km s⁻¹, with the exception of a narrow feature at $V_{\text{LSR}} = 679.9$ km s⁻¹ with a peak flux density of ~ 40 mJy beam⁻¹. The total integrated intensity estimated from these features lying at $V_{\text{LSR}} = 679\text{--}680$ km s⁻¹ and $V_{\text{LSR}} = 712\text{--}722$ km s⁻¹ is ~ 2.6 Jy km s⁻¹, which corresponds to ~ 7.4 L_⊙. We note a highly redshifted feature at the $\sim 3\sigma$ level centered at $V_{\text{LSR}} = 1138.1$ km s⁻¹ with a peak strength ~ 35 mJy beam⁻¹ (Fig. 1, 2). The corresponding fringe phases do not clearly show a consistent trend. Further, more sensitive observations are required to confirm this feature.

In Fig. 3, we compare the 321 GHz H₂O spectrum with a 22 GHz spectrum obtained on 2014 April 7 using the Deep Space Network 70-m antenna at Tidbinbilla. This observation was conducted at a spectral resolution of 31.25 kHz or 0.42 km s⁻¹ and with an rms of ~ 0.3 Jy. We conservatively estimate that the uncertainty in amplitude is up to 50 percent. The known strong variability of the 22 GHz maser emission in this galaxy, together with the ~ 1.8 years between the two observations, make it difficult to precisely compare the velocities of each feature between the 22 GHz and 321 GHz lines. In our 321 GHz observation, no feature was detected at or near the systemic velocity, while the 22 GHz spectrum in Fig. 3 shows a systemic feature, which is consistent with earlier single-dish measurements, (e.g., Greenhill et al. 1997). It should be noted that an asymmetry between the blueshifted and redshifted emission is commonly observed in H₂O megamasers, such as NGC 4258: Redshifted features are more numerous and are significantly more intense than the blueshifted features (e.g., Maoz & McKee 1998).

A comparison of the 321 GHz H₂O spectrum with the 22 GHz spectrum in Fig. 3, and similar spectra in the literature (Nakai et al. 1995; Braatz et al. 2003), indicates that the detected 321 GHz emission in the galaxy is similar to the features appearing in the 22 GHz maser spectra spanning $V_{\text{LSR}} = 643\text{--}714$ km s⁻¹, however, there is no direct correspondence between the velocities of the features in the two bands. In addition, in the published 22 GHz maser spectrum of Greenhill et al. (1997), the most redshifted velocity feature at $V_{\text{LSR}} = 774.4$ km s⁻¹ was tentatively detected, whereas there is no corresponding feature in either our 321 GHz or 22 GHz spectra. (Velocity values are converted from optical heliocentric to the LSR definition, using the relation $V_{\text{LSR}} = V_{\text{hel}} - 4.6$ km s⁻¹ in Greenhill et al. (1997)). Based on the ALMA data, the Gaussian-fitted phase-referenced position of the $V_{\text{LSR}} = 718.0$ km s⁻¹ peak emission is $\alpha(2000): 13^{\text{h}}05^{\text{m}}27^{\text{s}}.48$, $\delta(2000): -49^{\circ}28'05''.50$. Positional uncertainties of $0''.03$ are estimated. The position of the marginally significant redshifted emission at $V_{\text{LSR}} = 1138.6$ km s⁻¹ coincides with this peak within the uncertainties. According to the ALMA Cycle 0 capabilities, the positional errors are $\sim 10\%$ of the synthesized beam, corresponding to $0''.54/10 \sim 0''.054$ in our observation, and this can be taken as the most dominant source of error. The relative positions of other redshifted features coincide within uncertainties and the features remain unresolved at the angular resolution of $\sim 0''.54$, or ~ 30 pc. The position of the 22 GHz H₂O maser ($\alpha(2000): 13^{\text{h}}05^{\text{m}}27^{\text{s}}.48 \pm 0.02$, $\delta(2000): -49^{\circ}28'05''.4 \pm 0.1$; Greenhill et al. (1997)) coincides with those of the 321 GHz maser within uncertainties.

A 321 GHz submillimeter continuum image is obtained toward the nucleus of the galaxy, with a Gaussian-fitted peak position of $\alpha(2000): 13^{\text{h}}05^{\text{m}}27.47$, $\delta(2000): -49^{\circ}28'05''.42$ (with uncertainties of $\sim 0''.015$). The continuum peak flux density at this resolution is 136.5 mJy beam⁻¹, which is detected with an SNR of ~ 20 (Fig. 2) and an rms noise of about 7 mJy beam⁻¹, with a total continuum flux density of 543.3 mJy beam⁻¹. Thus, the approximate relative positional errors between the H₂O emission and the continuum peak, represented by the synthesized beam size divided by $2 \times \text{SNR}$ (Hagiwara et al. 2001) are $\sim 0''.055$ or 3.0 pc, within which the maser resides in the submillimeter continuum nucleus. Therefore, we conclude that the locations of the 321 GHz H₂O maser spots coincide with that of the submillimeter continuum peak within uncertainties of ~ 3.0 pc.

5. DISCUSSION

5.1. The 321 GHz continuum and new maser emission in NGC 4945

It is clear that the 321 GHz H_2O maser emission was detected toward the center of NGC 4945, an edge-on spiral housing a Type 2 Seyfert nucleus (Harnett & Reynolds 1985). The known, strong 22 GHz H_2O nuclear maser emission in this galaxy (Dos Santos & Lépine 1979) exhibits a disk-like structure around the nucleus (Greenhill et al. 1997). X-ray observations revealed that the nucleus of the galaxy is heavily obscured by foreground material (Iwasawa et al. 1993; Isobe et al. 2008), which is consistent with the fact that the maser excitation occurs in a region where there is abundant molecular material along our line of sight. The 321 GHz continuum emission shows a structure that is partly resolved in the northeast direction accompanying an elongated substructure in the north (Fig. 2). Given the synthesized beam size and position angle in Fig. 2, the major axis of the structure is real and similar to that of the CO galactic disk of $\sim 45^\circ \pm 2^\circ$ (Dahlem et al. 1993). The Spectral Energy Distribution of the galaxy (primarily from NED) suggests that the submillimeter continuum of the galaxy is dominated by dust emission: the photometric data points show that the continuum flux peaks at submillimeter wavelengths. Thus, it is likely that the most dominant submillimeter continuum component traces the dust lanes lying over the galactic disk, and that are heated by an AGN in the obscured nucleus. As discussed in the previous section, the 321 GHz H_2O maser emission coincides with the nuclear continuum peak, and the maser is likely to be associated with AGN-activity in the galaxy by analogy with the case of 22 GHz maser in the galaxy. However, we cannot rule out the possibility that the maser emission originates in star-forming activity or nuclear starbursts. The angular resolution of our Cycle-0 observations were not sufficient to resolve these maser spots and clarify the origin of the maser emission. The 22 GHz and 183 GHz H_2O emission in the LINER/Seyfert Type 2 galaxy, NGC 3079 occur in a similar velocity range (Humphreys et al. 2005). This suggests that these masers are located in similar regions, at least, in our line of sight. As with the case of the masers in the Circinus galaxy discussed in Hagiwara et al. (2013), the difference of locations of the 321 GHz and 22 GHz H_2O maser must be addressed also for NGC 4945.

Simultaneous monitoring of these 22 GHz and 321 GHz transitions that are ortho- H_2O would help to clarify the excitation mechanism of the masers, by constraining radiative transfer models (e.g. Humphreys 2007).

5.2. Submillimeter H_2O masers in AGN

Presently, only a handful of extragalactic submillimeter H_2O masers have been detected. In this observing program, submillimeter H_2O masers were discovered in two of the five AGNs. The detections are from two nearby AGN hosting the 22 GHz nuclear masers with the strongest extragalactic maser flux densities ($\gtrsim 10$ Jy) known to date (Dos Santos & Lépine 1979; Greenhill et al. 2003; Hagiwara et al. 2013). The detection of the submillimeter H_2O masers can therefore be predicted for the strongest nuclear masers known at 22 GHz in the northern sky, primarily in the nearby AGN, NGC 4258 and possibly in NGC 3079, although the latter is difficult to observe with ALMA. The non-detections for the other AGN in our list might not be surprising, as their 22 GHz flux densities are an order of magnitude smaller than those from strongest nuclear masers.

We did not detect maser emission at either frequency for NGC 5793. It is known that 325 GHz H_2O masers in star-forming regions are strongly inverted like 22 GHz masers (Menten et al. 1990b). The 22 GHz maser in this galaxy is not as bright as the other strong nuclear masers, and so the non-detection of the maser is not surprising.

In previous studies of H_2O masers in star-forming regions, the total velocity spread of 321 GHz H_2O masers is observed to be smaller than that of 22 GHz H_2O maser (Menten et al. 1990a), while our data marginally detected highly redshifted features (redshift up to ~ 600 km s $^{-1}$) in both the Circinus galaxy and NGC 4945, from which we can speculate that extragalactic submillimeter masers are tracing phenomena which do not originate from star-forming activity but rather from AGN activity. The variability of the submillimeter H_2O maser emission in the Circinus galaxy was discussed in Hagiwara et al. (2013), who inferred that the 22 GHz maser was in a flaring state in mid-2012; significant increases of the maser flux density up to 50–70 Jy were measured in 2012 June and September (note that the flux values include large uncertainties). This is the largest flare ever reported in this galaxy (e.g., Greenhill et al. 1997; Braatz et al. 2003). Our detection of the 321 GHz H_2O maser in the Circinus galaxy might be due to the large flare in 2012. Likewise, the detection threshold of submillimeter H_2O maser may depend strongly on the flux variability.

5.3. High-Velocity Dense Gas in NGC 4945

Greenhill et al. (1997) estimated the central binding mass in NGC 4945, by assuming the rotation of gases on a Keplerian disk of 150 km s $^{-1}$ at 0.3 pc from the central engine and a disk inclination of 90° , which yielded a black hole mass of $1.4 \times 10^6 M_\odot$. In our observations, a highly redshifted velocity feature at $V_{\text{LSR}} = 1138.6$ km s $^{-1}$ is marginally detected. In their analysis of this data set, Pesce et al. (2016) note that this velocity range is impacted by higher atmospheric absorption resulting in a somewhat higher noise level, and so further observations are required to confirm this feature.

Table 1. Summary of a search for extragalactic submillimeter H₂O emission

Source	RA ^a (J2000)	DEC ^a (J2000)	D ^b (Mpc)	Date ^c	ν^d (GHz)	N _A ^e	t _{on} ^f (min)	θ_b^g (PA ^h) (arcsec ² , °)	1 σ^i (mJy)
NGC 1068	02 ^h 42 ^m 40 ^s .770	−00°00′47″.84	12.5	June 2-6	319.07	21	39	0.61×0.44 (42)	4–6
NGC 1386	03 ^h 36 ^m 46 ^s .237	−35°59′57″.39	10.6	June 5	319.36	29	11	0.67×0.54 (−27)	10–15
NGC 4945	13 ^h 05 ^m 27 ^s .279	−49°28′04″.44	11.1	June 3	319.68	18	14	0.54×0.51 (11)	8–11
Circinus	14 ^h 13 ^m 09 ^s .906	−65°20′20″.46	4.2	June 3	319.82	18	18	0.66×0.51 (−17)	9–11
NGC 5793	14 ^h 59 ^m 24 ^s .807	−16°41′36″.55	51.1	June 3	316.59	21	6	0.56×0.47 (47)	11–13
NGC 5793	14 ^h 59 ^m 24 ^s .807	−16°41′36″.55	51.1	June 3	320.47	21	19	0.66×0.46 (−89)	8–11

^a Interferometry phase center positions in R.A. and Declination^b Luminosity distances, adopted from NED^c Date of observations in 2012^d Observing frequencies at channel 0 in each spectral window^e Number of the 12-m antenna used in the ALMA observations^f On-source time for the target source^g Synthesized beam size^h The beam position angleⁱ rms noise values in a 488.3 kHz spectral resolution in the clean image, depending on channel

We note, however, that if the 1138 km s^{−1} feature, redshifted by ~ 585 km s^{−1} from the systemic velocity, is real, the maser is located at a distance of ~ 0.020 pc from the central engine, based on the Keplerian ($v \propto r^{-0.5}$) rotating disk model in [Greenhill et al. \(1997\)](#). This corresponds to $\sim 1.5 \times 10^5$ Schwarzschild radii for a 1.4×10^6 M_⊙ black hole. Similarly, the most redshifted velocity feature in the Circinus (redshifted by ~ 635 km s^{−1} from the systemic) is estimated to be at a radius of ~ 0.018 pc ($\sim 1.2 \times 10^5$ Schwarzschild radii for a 1.7×10^6 M_⊙ black hole) ([Hagiwara et al. 2013](#)). One can speculate that the high-velocity dense gas found in other AGNs in future observations is tracing the molecular material closest to central engine. High-resolution imaging of submillimeter masers promises to be a powerful tool to further explore the gas that probes the AGN circumnuclear region on parsec- and sub-parsec scales. Since the masers detected in this program are unresolved, their spatial structures have yet to be explored for studying the circumnuclear regions of their host galaxy. ALMA has progressively achieved longer baselines and has attained a maximum angular resolution of ~ 30 mas (corresponding to 1.5 pc at a distance of 10 Mpc) in band 7 (e.g., [ALMA Partnership et al. 2015a,b](#)). Future observations will be able to resolve the circumnuclear gas of AGN on scales that are becoming comparable to VLBI observations at 22 GHz.

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Facilities: ALMA, Tidbinbilla 70-m telescope

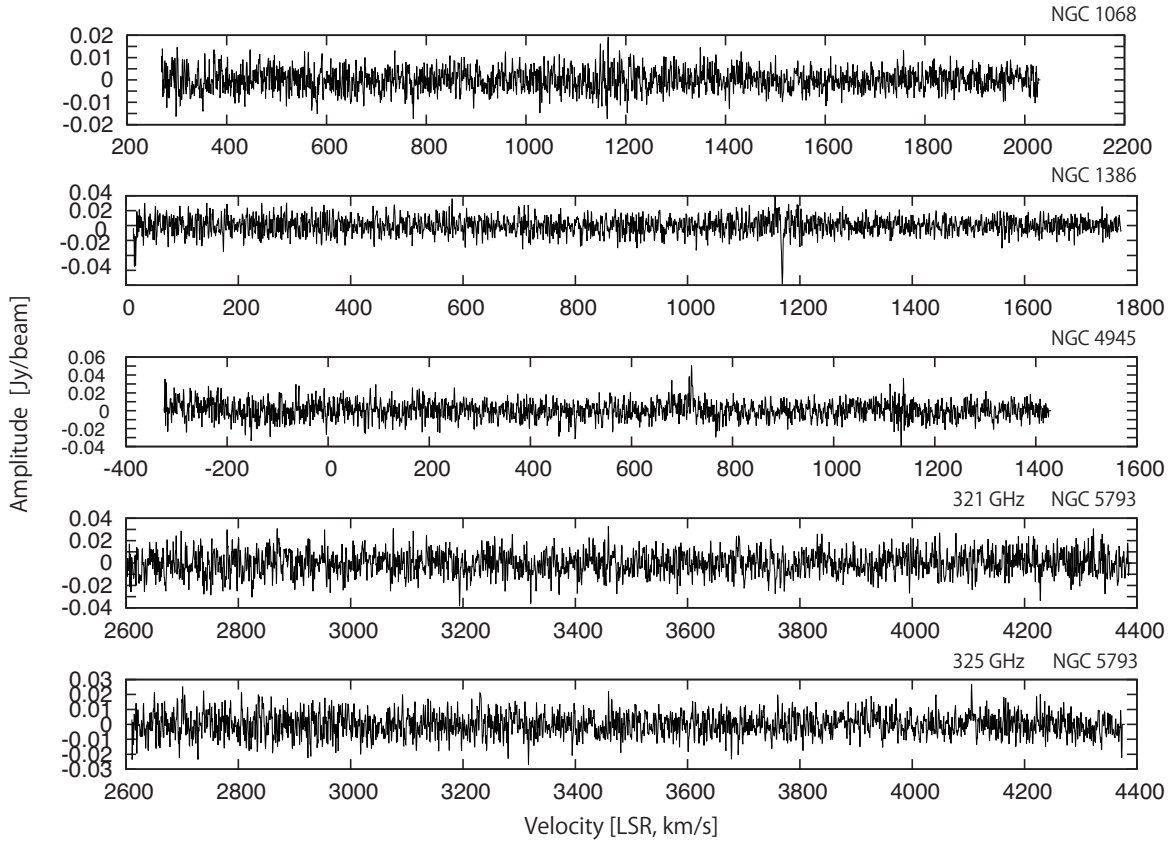


Figure 1. Spectra of NGC 1068, NGC 1386, NGC 4945, and NGC 5793 at 321 GHz and a spectrum of NGC 5793 at 325 GHz, obtained by the ALMA between 2012 June 2–6. All of these spectra were obtained toward the peak of the submillimeter continuum emission centered at each observing frequency. The negative components seen in the NGC 1386 spectra are not real, and arise from insufficient amplitude calibration for those channels.

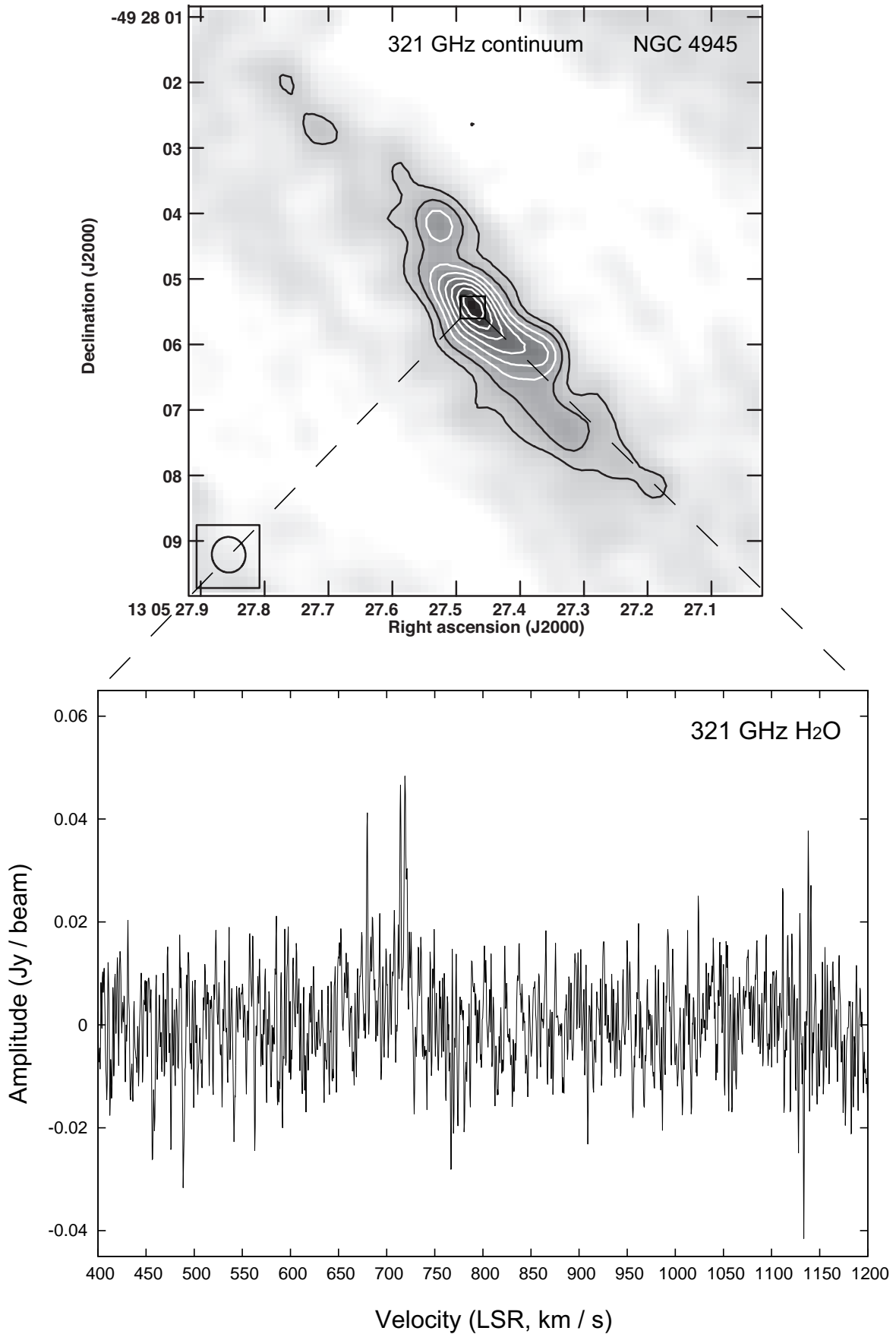


Figure 2. 321 GHz continuum image and the spectrum of H₂O maser in NGC 4945 toward the center of the continuum, obtained by ALMA on 2012 June 3. Intensity-scales are denoted by contours and grey-scales: The contour levels are $-3, 3, 5, 7, 9, 11, 13, 15, 17, 19$ of $7.35 \text{ mJy beam}^{-1}$ ($\sim 1 \sigma$), the peak flux density is $136.5 \text{ mJy beam}^{-1}$, and the grey-scale ranges from 10 to $136.0 \text{ mJy beam}^{-1}$. The synthesized beam is shown in the bottom left. The total velocity coverage of the spectrum is $V_{\text{LSR}}=400\text{--}1200 \text{ km s}^{-1}$. The maser spectrum is obtained toward the region marked by a box on the continuum image.

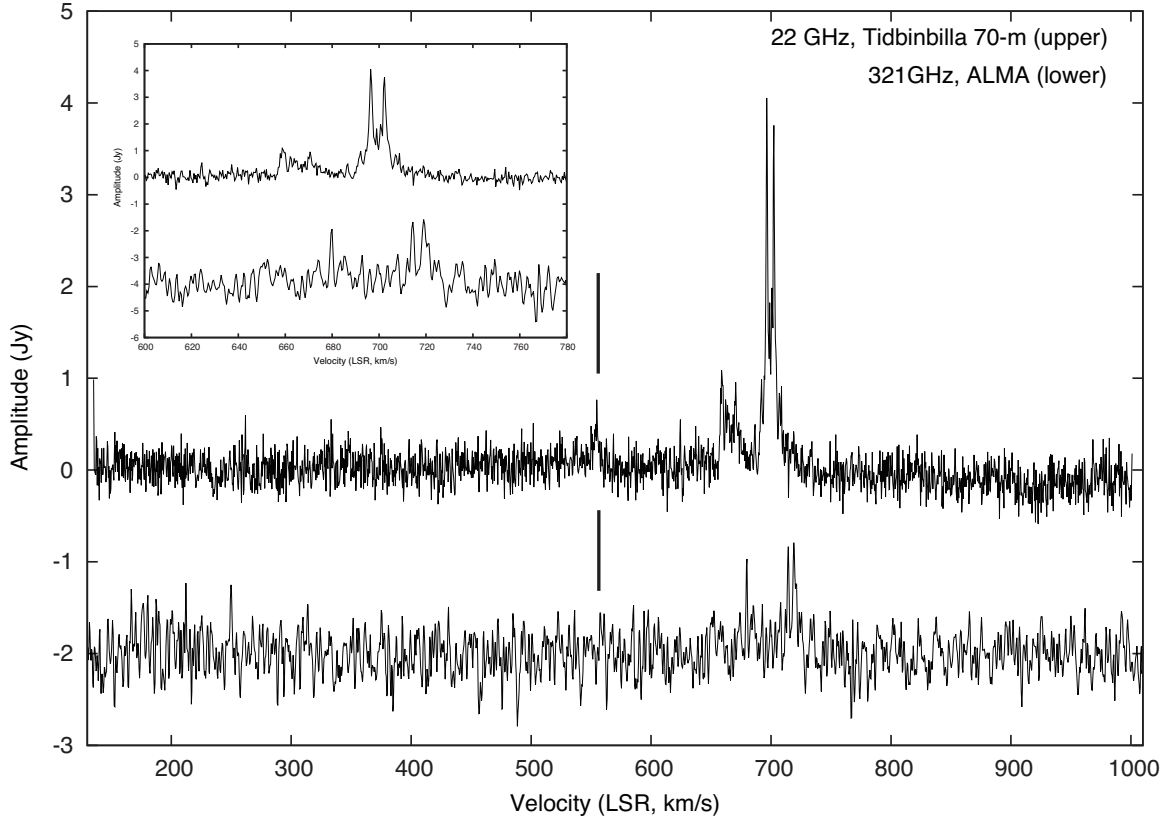


Figure 3. Comparison of H_2O maser spectra in the 321 GHz and 22 GHz transitions toward the continuum nucleus of NGC 4945 in velocities spanning from $V_{\text{LSR}}=130 \text{ km s}^{-1}$ to $V_{\text{LSR}}=1100 \text{ km s}^{-1}$. The 22 GHz spectrum was obtained with the Deep Space Network (DSN) 70-m antenna at Tidbinbilla on 2014 April 7. The amplitude scale of the 321 GHz spectrum is multiplied by a factor of 25 with an offset of 2 Jy for display purposes. The systemic velocity of NGC 4945 is denoted by vertical bars. The inset displays the two maser spectra in velocities from $V_{\text{LSR}}=600\text{--}780 \text{ km s}^{-1}$, where the amplitude scale of the 321 GHz spectrum is multiplied by a factor of 50 and an offset of 4 Jy applied for clarity.

REFERENCES

- ALMA Partnership, Brogan, C. L., Pérez, L. M., Hunter, T. R., et al. 2015a, *ApJL*, 808, L3
- ALMA Partnership, Fomalont E. B., Vlahakis C., et al. 2015b, *ApJL*, 808, L1
- Braatz, J. A., Wilson, A. S., Henkel, C., Gough, R., & Sinclair, M. 2003, *ApJS*, 146, 249
- Cernicharo, J., Pardo, J. R., Weiss, A. 2006, *ApJ*, 646, L49
- Claussen, M. J., & Lo, K.-Y. 1986, *ApJ*, 308, 592
- Dahlem, M., Golla, G., Whiteoak, J. B., Wielebinski, R., Hüttemeister, S., & Henkel, C. 1993, *A&A*, 270, 29
- Deguchi, S. 1977, *PASJ*, 29, 669
- Dos Santos, P. M., & Lépine, J. R. D. 1979, *Nature*, 278, 34
- Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, *ApJ*, 346, 983
- Gray, M. D., Baudry, A., Richards, A. M. S., Humphreys, E. M. L., Sobolev, A. M., Yates, J. A., 2016, *MNRAS*, 456, 374
- Greenhill, L. J., Moran, J. M., Reid, M. J., Menten, K. M., & Hirabayashi, H. 1993, *ApJ*, 406, 482
- Greenhill, L. J., Moran, J. M., & Herrnstein, J. R. 1997, *ApJ*, 481, L23
- Greenhill, L. J., & Gwinn, C. R. 1997, *Ap&SS*, 248, 261
- Greenhill, L. J., et al. 2003, *ApJ*, 582, L11
- Greenhill, L. J., et al., 2009, *ApJ*, 707, 787
- Hagiwara, Y., Kohno, K., Kawabe, R., & Nakai, N. 1997, *PASJ*, 49, 171
- Hagiwara, Y., Diamond, P. J., Nakai, N., & Kawabe, R. 2001, *ApJ*, 560, 119
- Hagiwara, Y. 2007, *AJ*, 133, 1176
- Hagiwara, Y. Miyoshi, M., Doi, A., Horiuchi, S., 2013, *ApJ*, 133, 1176
- Hagiwara, Y., Horiuchi, S., Doi, A., Miyoshi, M., 2015, Japan Astronomical Society, Annual Meeting Autumn Session, 2015 September 9-11, Konan University, Hyogo, Japan, <http://www.asj.or.jp/nenkai/2015b/pdf/S20a.pdf> (in Japanese)
- Harnett, J. I., & Reynolds, J. E. 1985, *MNRAS*, 215, 247
- Humphreys, E. M. L., Greenhill, L. J., Reid, M. J., Beuther, H., Moran, J. M., Gurwell, M., Wilner, D. J., Kondratko, P. T. 2005, *ApJ*, 634, L133
- Humphreys, E. M. L. 2007, *Astrophysical Masers and their Environments* (IAU Symp. 242), ed. Chapman, J. M. & Baan, W. A. (Cambridge: Cambridge Univ. Press), vol.242, 471
- Isobe, N., Kubota, A., Makishima, K., Gandhi, P., Griffiths, R. E., Dewangan, G. C., Itoh, T., Mizuno, T. 2008, *PASJ*, 60, 241
- Iwasawa, K., et al. 1993, *ApJ*, 409, 155
- Maoz, E., McKee, C. F. 1998, *ApJ*, 494, 218
- Menten, K. M., Melnick G. J., & Phillips, T. G. 1990a, *ApJ*, 350, L41
- Menten, K. M., Melnick G. J., Phillips, T. G., & Neufeld, D. A. 1990b, *ApJ*, 363, L27
- Menten, K. M. & Melnick G. J., 1991, *ApJ*, 377, 647
- Miyoshi, M. Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., Inoue, M. 1995, *Nature*, 373, 127
- Nakai, N., Inoue, M., Miyazawa, K., Miyoshi, M., & Hall, P. 1995, *PASJ*, 47, 771
- Neufeld, D. A. & Melnick, G. J. 1990, *ApJ*, 352, L9
- Neufeld, D. A. & Melnick, G. J. 1991, *ApJ*, 368, 215
- Neufeld, D. A., Lepp, S., & Melnick, G. J. 1995, *ApJS*, 100, 132
- Pesce, D. W., Braatz, J. A., Impellizzeri, C. M. V., 2016 *ApJ*, submitted (arXiv:1604.03789)